Operating the Dual-Orbiter GRAIL Mission to Measure the Moon's Gravity

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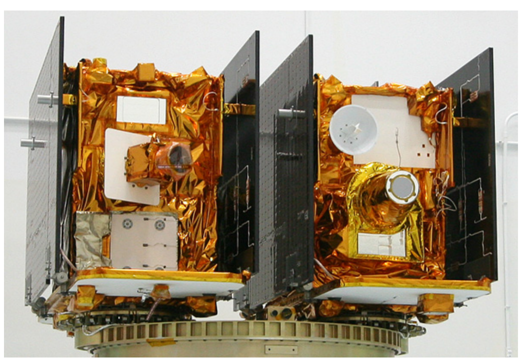
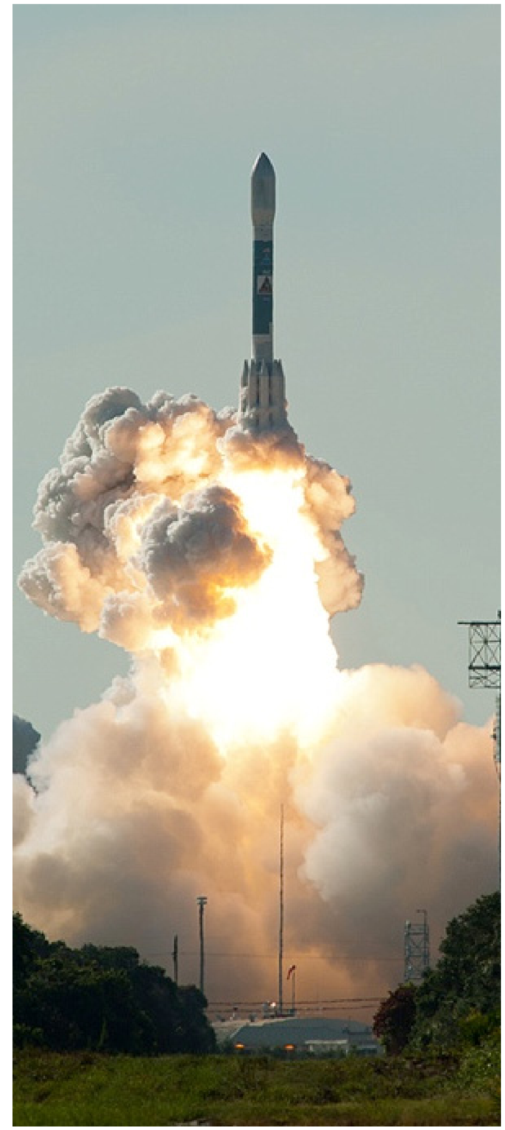
Introduction

- Gravity Recovery and Interior Laboratory (GRAIL) mission’s twin orbiters launched from Florida on September 10, 2011, on a Delta-II launch vehicle.
- Prime mission has just completed its 3-month science phase to determine the Moon’s interior structure, from crust to core.
- Mission is operated jointly by JPL in Pasadena, California and Lockheed Martin in Denver, Colorado.
- Mission operations have gone very smoothly due to extensive pre-launch planning and checkout.
- GRAIL benefits from extensive heritage from previous JPL/LM planetary missions, and operational heritage of the GRACE mission that measures the earth’s gravity.





Mission Overview

- GRAIL has completed its prime mission!
- Since launch, 28 propulsive maneuvers have been successfully completed by the two orbiters to reach and maintain science configuration.

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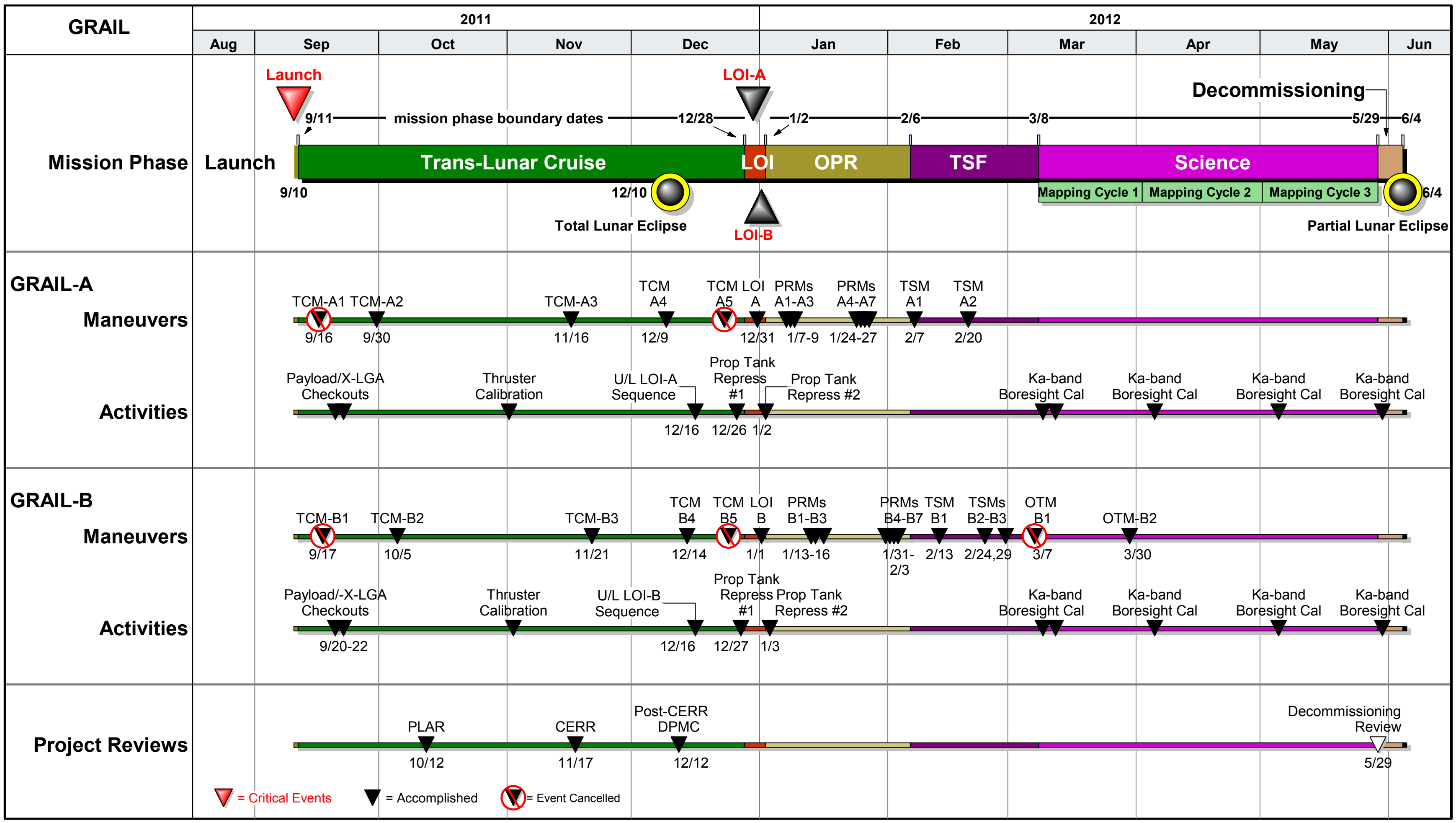
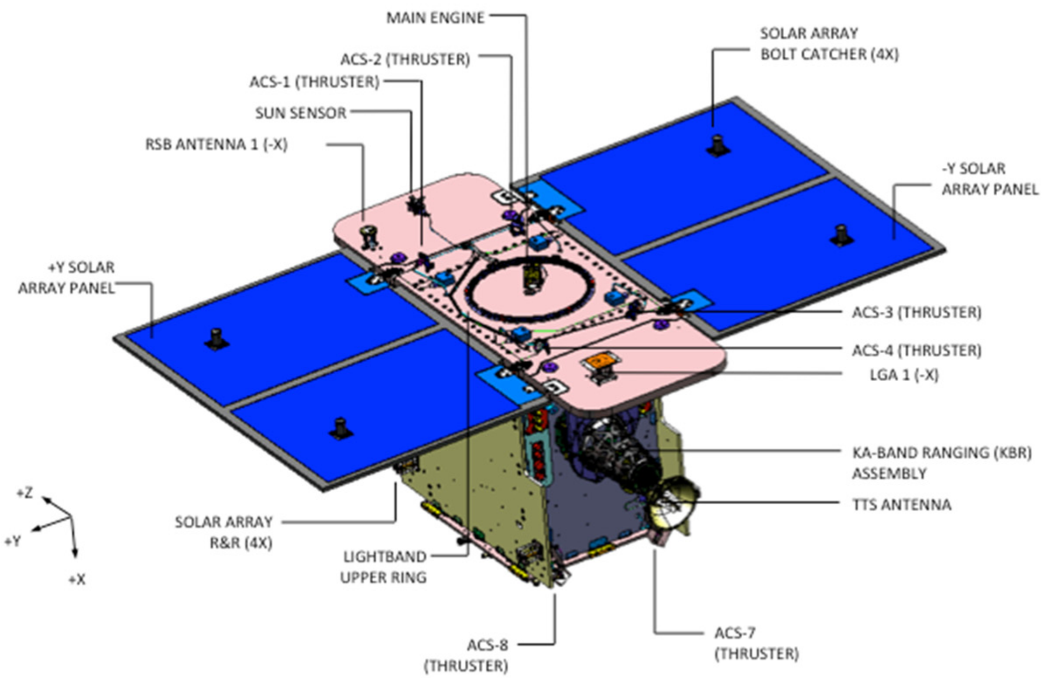


Orbiter Description: GRAIL-A (GR-A) and GRAIL-B (GR-B)



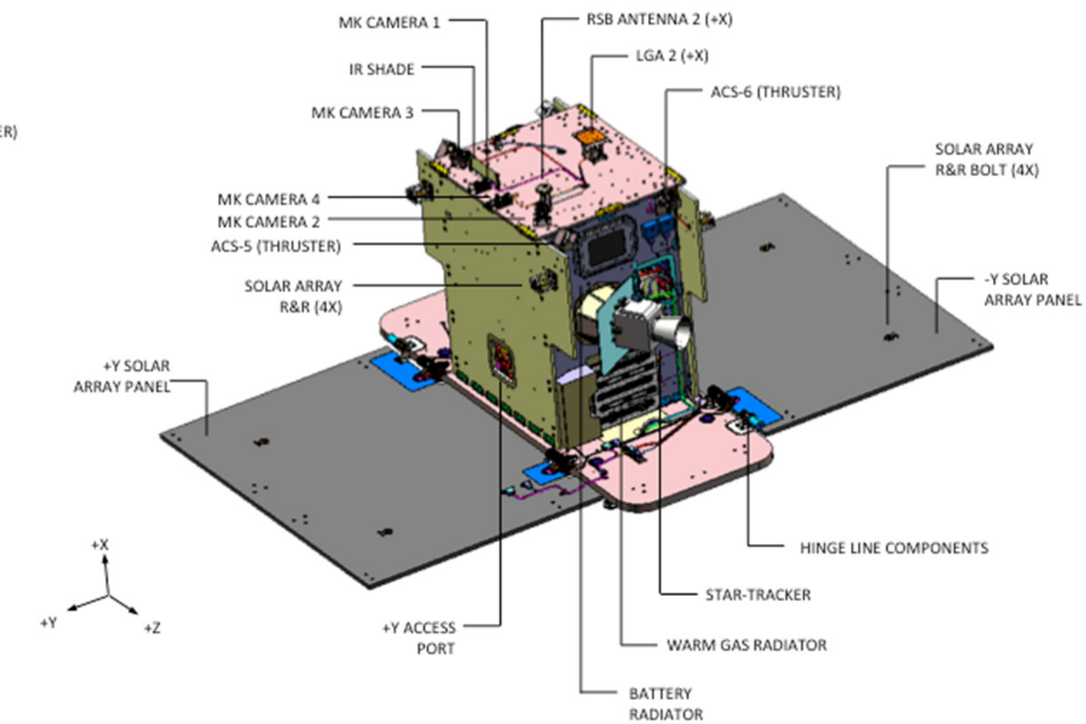
Named "Ebb" and "Flow" by students from Emily Dickinson Elementary School in Bozeman, Montana.

Payload features:

- **Science payload is Lunar Gravity Ranging System (LGRS) that transmits and receives Ka-band (ranging) & S-band (timing) signals.**
- **Education and Public Outreach (E/PO) MoonKAM system with four camera heads.**

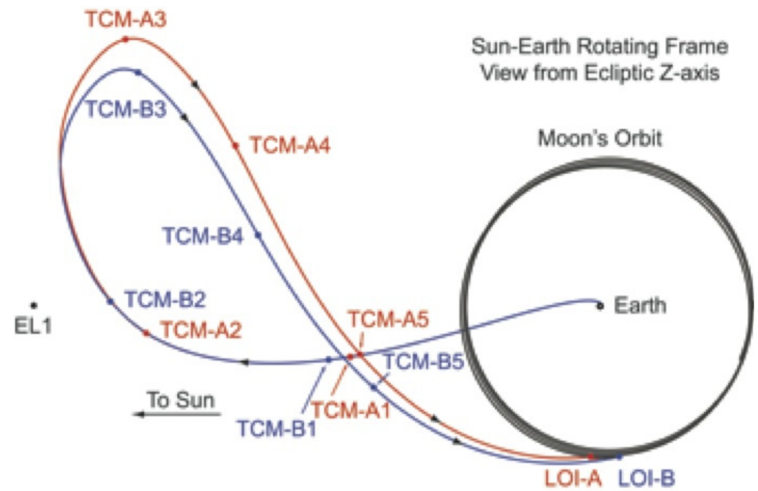
Spacecraft features:

- **3-axis stabilized, reaction wheels & warm gas thrusters for control**
- **Star Tracker & gyros (IMU) for attitude determination**
- **22-N hydrazine main engine**
- **Two Low Gain Antennas (LGA)**
- **Avionics & flight software based on MRO**

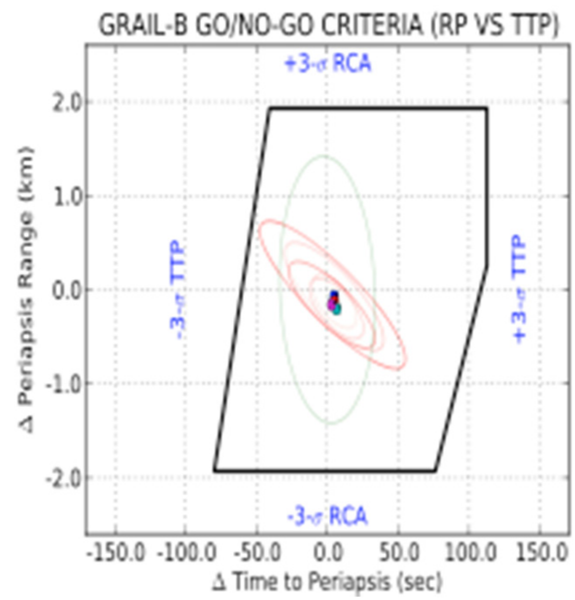


Trans-Lunar Cruise (TLC) Phase Operations

- Five planned Trajectory Correction Maneuvers (TCMs) per orbiter during TLC.
  - TCM 1s not required due accurate LV injection.
  - TCM 2-4 performed within specification to target desired LOI
  - TCM-5s, statistical, were not required, meeting established "Go/No-Go" criteria (right)
- Extra Payload Checkout added after TCM-1 cancelled.
  - With separation of 500 km, orbiters were pointed at each other with LGRS on on Sept. 22.
  - Orbiters successfully received each others S-band and Ka-band signals.
- LOI maneuver planning began after TCM-2s, assuming remaining TCMs executed nominally.
  - Pass 2 update after TCM-3 was not required
  - LOI preparation included contingency design in case repressurization was not successful.



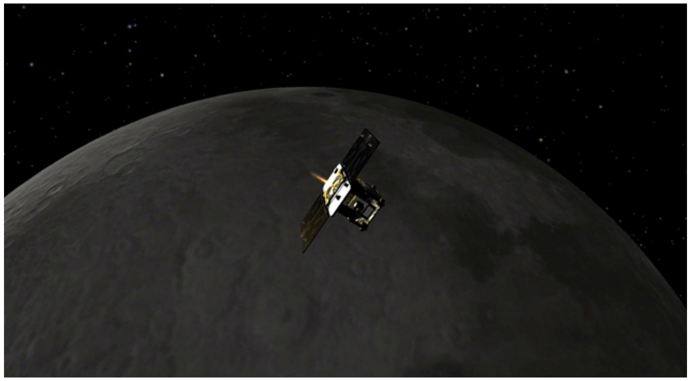
LOW-ENERGY CRUISE TRAJECTORY

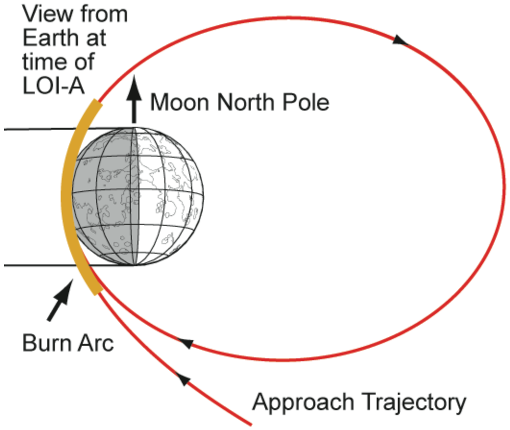


TCM-5 "GO/NO-GO" CRITERIA

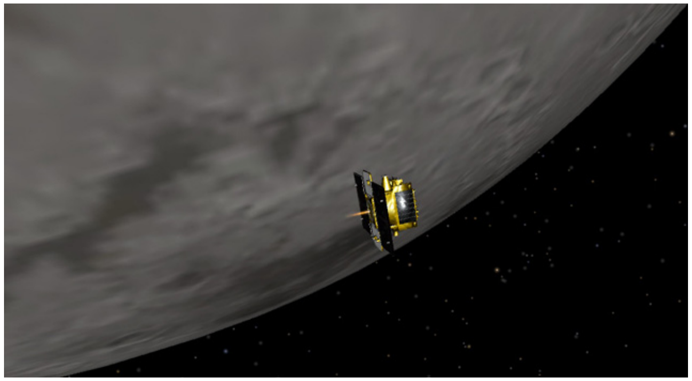
Lunar Orbit Insertion (LOI) Operations

- Propellant Tank Repressurization planned for Dec. 23, 2011 was delayed.
  - Firing a pyro-valve, and then opening a latch-valve releases Helium into system.
  - Zero-bias shift to pressure transducer calibration occurred during GR-A and GR-B pyro-valve firings.
  - Similar effect occurred on Mars Odyssey mission.
  - Repressurization was finally completed on Dec. 26 (GR-A) & Dec. 27 (GR-B), including updated calibration curve zero-point values.



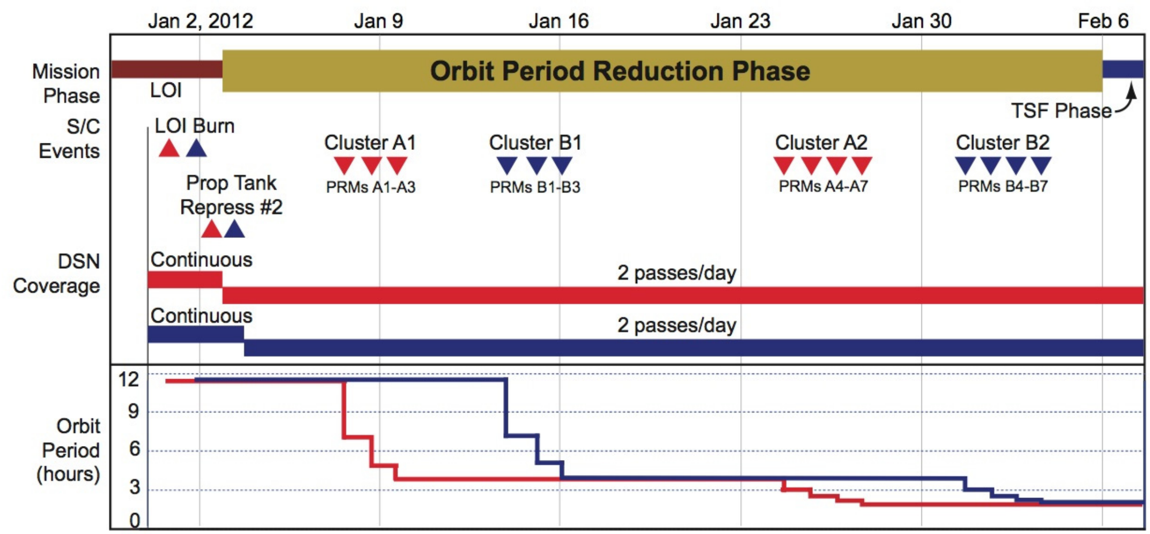


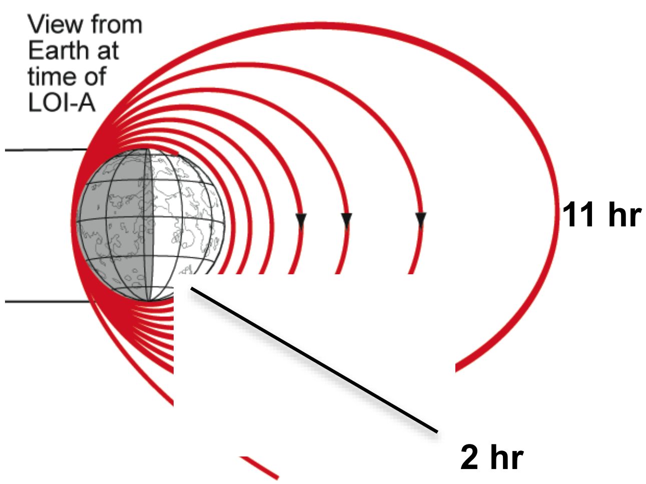
- Successful LOI maneuvers conducted on Dec. 31, 2011 (GR-A) and Jan. 1, 2012 (GR-B).
  - ~38 minute burns over constant pitch rate, imparted 190 m/s of delta-V, and consumed 24 kg. of fuel.
  - Burn durations shorter than expected: 71 sec for GR-A and 25 sec. for GR-B.
    - Propellant motion shifted orbiter center-of-gravity, resulting increased ACS-thruster duty cycle, thus heating the gas generator.
    - Heating resulted in higher propellant tank pressures.



Orbit Period Reduction (OPR) Phase Operations

- 7 Period Reduction Maneuvers (PRMs) reduce post-LOI orbit period from 11.5-hours down to 1.9 hours.
  - Maneuvers divided into two clusters on each orbiter.
  - Maneuvers in each cluster conducted 1-day apart with same magnitude and direction.

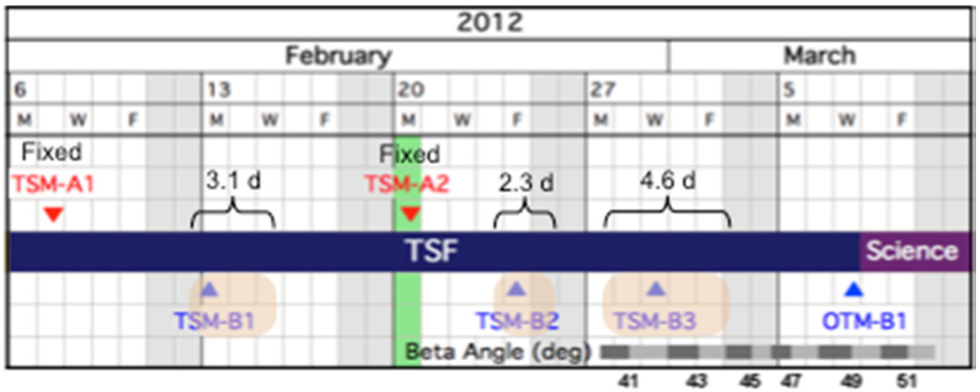




- Star Tracker obscuration anomaly
  - During OPR, the GR-A experienced several anomalies where the Star Tracker locked onto a bad solutions as the moon passed through its field-of-view.
  - The ultimate solution was to command the Star Tracker into “standby” mode whenever the moon entered its field of view.
  - Once in science configuration, the orbiters are nadir pointed, avoiding any intrusion of the moon into the Star Tracker field-of-view.

Transition to Science Formation (TSF) Phase Operations

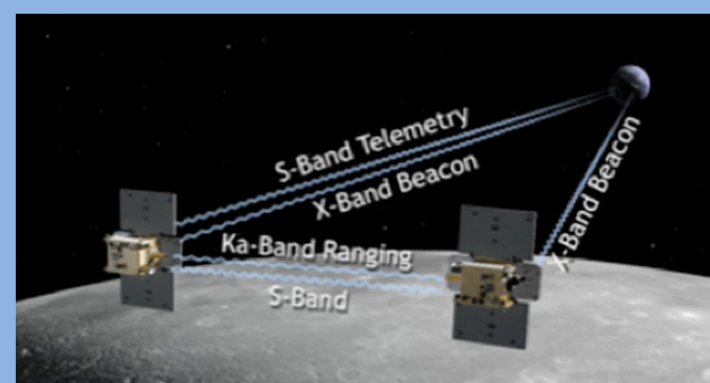
- 5 Transition-to-Science Maneuvers (TSMs) rendezvous the twin-orbiters in their science orbits, with GR-B leading GR-A.
- Uncertainties in maneuver execution at the end of OPR result in in multi-day windows for predicted TSM execution.



TSF TIMELINE WITH MANEUVER EXECTION WINDOWS.

- TSM-A1 and TSM-B1 establish the science orbit, but the orbiters are too far apart to establish link.
- TSM-A2 allows the orbiters to slowly approach each other.
- TSM-B2 slows the rate of approach once close.
- Finally, TSM-B3 halts relative drift rate between the orbiters at 75 km.

- **On March 1, the orbiters were commanded from sun-point to orbiter-point, establishing S-band & Ka-band inter-orbiter links.**
- **OTM-B1 was not required due accuracy of TSM-B3.**



GRAIL SCIENCE CONFIGURATION

Science Operations

- Science data collection began 1 week early due to favorable power & thermal performance.
- Near-polar, near-circular orbit with a mean altitude of 55 km.
- During the 82-day science phase, the Moon rotates three times, resulting in 3 mapping cycles.
- During mapping cycle 1, the separation distance drifted from 75 to 216 km. After OTM-B2, separation distance decreased to 87 km at end of science.

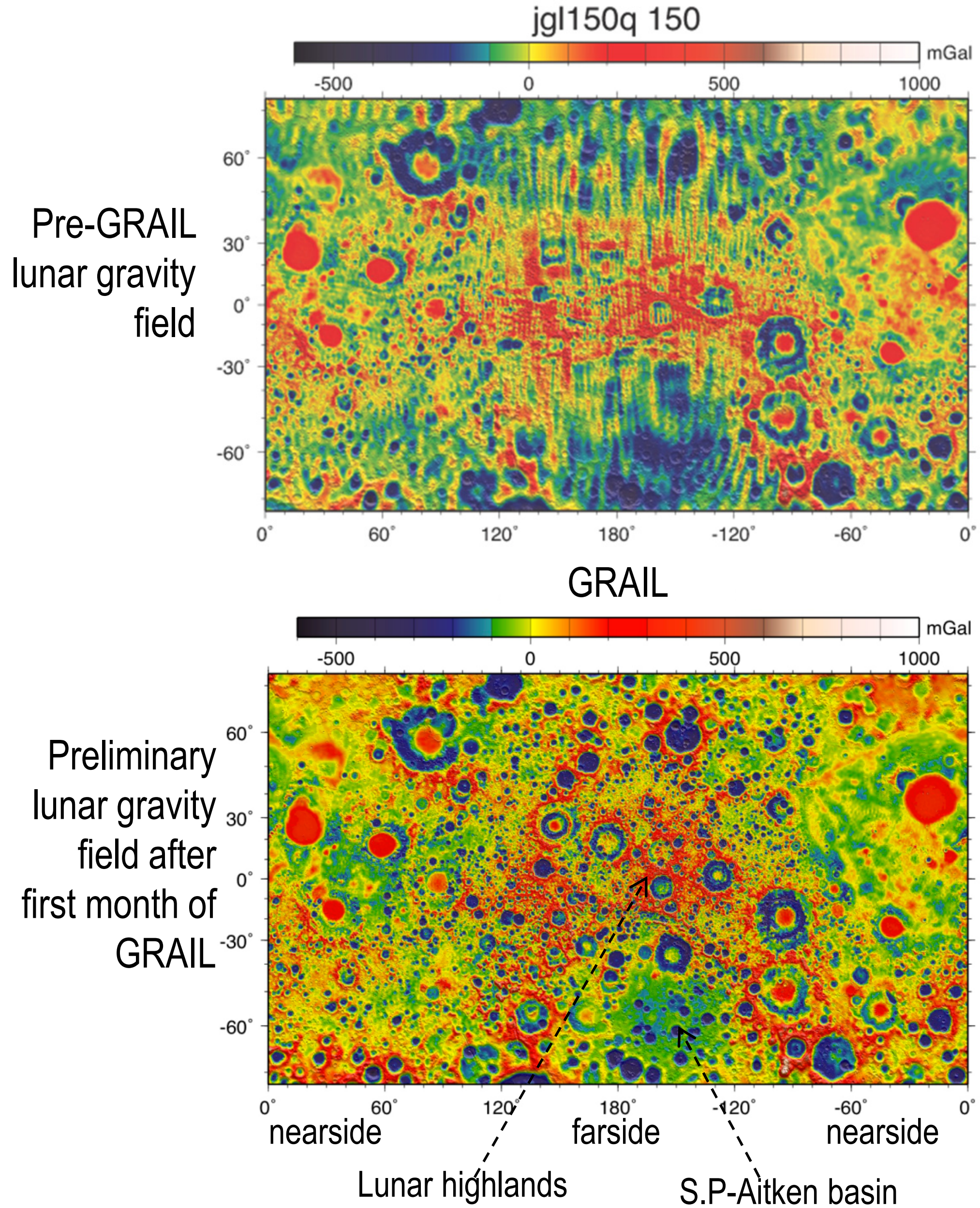
Key Operational Findings during Science

- Solar activity effect on orbiters:
  - USO frequency shifts & GPA reboot
  - MoonKAM over-current condition
  - MoonKAM data interruption
- Angular momentum accumulation due to gravity gradient torques
  - Became dominant torque in middle of science phase without solar pressure torque.
  - Commanded extra reaction wheel "desats".
- Telecommunications interference attributed to multi-path effects
  - Reflected signals from moon's surface periodically result in uplink errors.

- GRAIL is NASA's first planetary mission with instruments fully dedicated to education and public outreach.
- MoonKAM operations led by Sally Ride Science at the University of San Diego
  - 3116 student operations centers at 2853 unique schools.
  - https://moonkam.ucsd.edu/

Preliminary GRAIL Lunar Gravity Field

- The most accurate global gravity model of the Moon to date has been developed from the first month of GRAIL data
- The measurements uncertainty is improved by one order of magnitude on the near side and two orders of magnitude on the far side
- The model reveals details of the lunar landscape, particularly over the lunar far side, showing the gravity signals of craters and basins not seen before
- Nearly all craters larger than 25 km diameter display gravity signals indicative of the processes of formation



Extended Mission Preview

- Extended mission through December 2012, allows collection of higher resolution (factor of 2) gravity data by flying at an even lower altitude (23-km. mean).
- Maintained via weekly Eccentricity Correction Maneuvers (ECMs) on both orbiters, followed by an OTM the next day.
- Extended mission contains 45 baseline maneuvers. Orbital Circularization Maneuvers (OCMs) performed on schedule.

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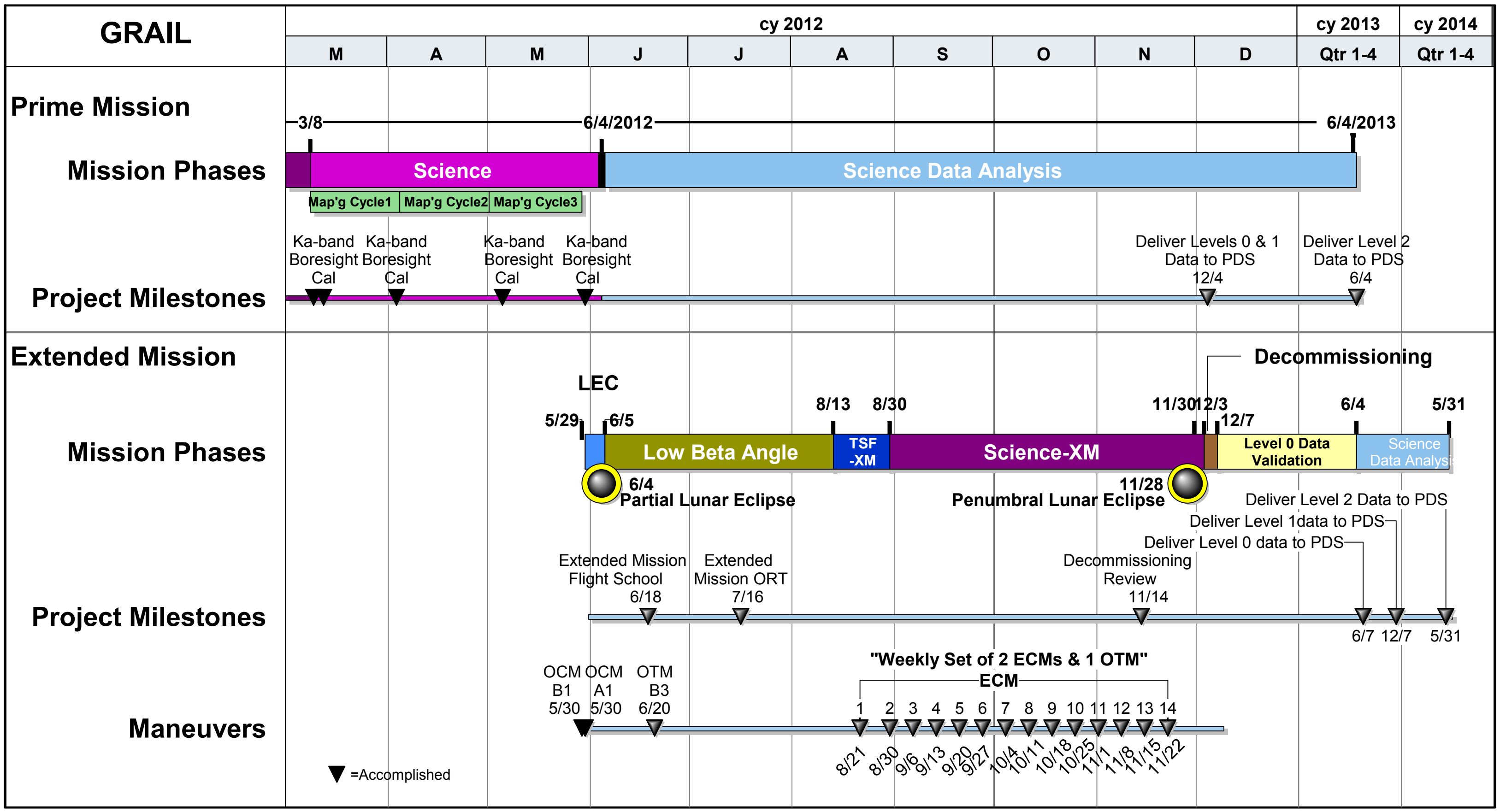
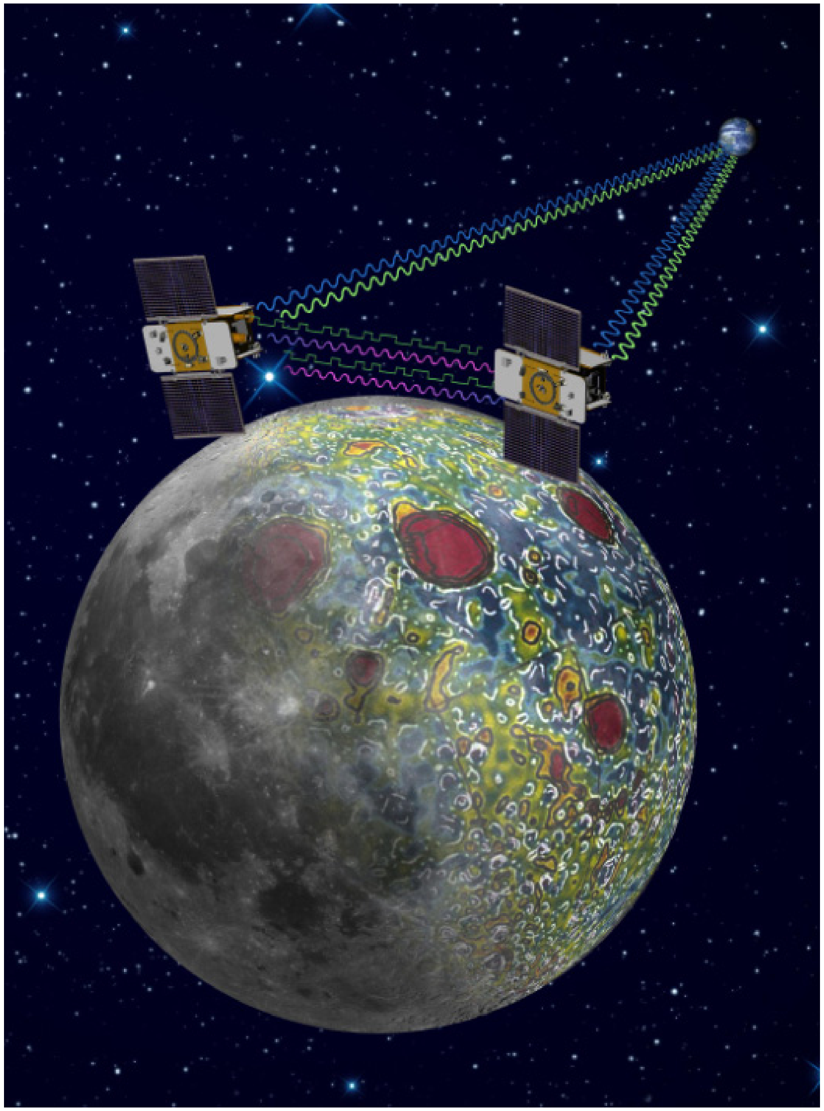


Conclusion



- The GRAIL mission is on track to satisfy all prime mission requirements.
- The performance of the orbiters and payload has been exceptional.
- Detailed pre-launch operations planning and validation have paid off.
- Prime mission timeline has been conducted almost exactly as laid out in the mission plan.
- Flight experience in the prime mission puts the flight team in a good position for completing the challenges of the extended mission where the science payoff is even greater.

Acknowledgements

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Affiliation is JPL unless noted.